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BASE TECHNOLOGY STIRLING ENGINE MILITARY APPLICATIONS ASSESSMENT

ARGONNE NATIONAL LABORATORY
COMPONENTS TECHNOLOGY DIVISION
9700 SOUTH CASS AVENUE
ARGONNE, ILLINOIS 60439

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Final Report for Period June 1983 - September 1983

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AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEM COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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The design of an advanced Stirling engine is considered for potential use in Air Force mobile electric power generator sets. The prospects for acceptable reliability appears good due to new appraoches to recognized Stirling problem areas; sealing, heater head and control. The present design appears suitable for a 30kW set, but Air Force needs would be best suited by development of a 60kW unit. Standardization would be facilitated by using the 60kW Stirling engine and associated auxiliaries in a 30kW set. Final design drawings have been completed in the 30kW engine but construction and tests are required to establish that both design criteria for the engine and mobile power requirements are met.

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PREFACE

This final report presents the results of research completed for the Energy Conversion Branch (POO), Aerospace Power Division (PO) Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL), Wright-Patterson AFB, Ohio 45433 under Military Interdepartmental Purchase Request FY1455-83-N0629 "Base Technology Stirling Engine Military Application Assessment."

The work reported herein was performed during the period 1 June 1983 to 30 September 1983 under the direction of the Project Engineer, Ms. Valerie Van Griethuysen.

The author of this final report was Dr. James G. Daley.

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SECTION I

INTRODUCTION

Stirling engines were originally investigated for use in tactical electric power generator sets in the mid 1960s when the U.S. Army Mobility Equipment Research and Development Command at Fort Belvoir (presently Belvoir Research and Development Center) procured a 3 kW set manufactured by General Motors as a licensee of N. V. Philips of the Netherlands.[1] Interest in Stirling engines for this application has continued and procurement is presently underway at Fort Belvoir for a 3.0 kW Stirling set. Procurement has also been initiated at Fort Belvoir for a 5 kW set.

Stirling-powered sets have several attractive attributes, the most important being the ability to operate on any logistic fuel. Other favorable attributes are: high efficiency (especially at part load), quiet and low vibration operation, and low IR emission. Since the combustion system is external to the engine, derating due to altitude and temperature is not necessary; also since combustion products are also external, the moving parts of the engine are in an environment free from combustion product contaminants. Offsetting these desirable features is the fact that Stirling technology has not yet emerged from the laboratory to becoming a commercially available product. Also, the additional complexity of Stirling engines (compared to prime movers in the present standard family of generator sets) has implications for poorer reliability and higher cost. Stirling engines reject most of their waste heat through the cooling system and must be liquid-cooled. The number of important system components and disposition of reject heat is indicated in Fig. 1.

Air Force use of mobile electric power (MEP) units has been primarily in the higher power ranges (30 kW and up). Argonne National Laboratory has been directing a program for the Department of Energy to develop Stirling technology that has included a project on a Base Technology Stirling Engine (BTSE) (see Chapter II) that offers new design approaches to Stirling engines in the higher power range. The BTSE design is felt to be applicable in the range 10 kW to 370 kW. This report assesses the current design, which is nominally 25 kW, for its applicability to Air Force requirements.

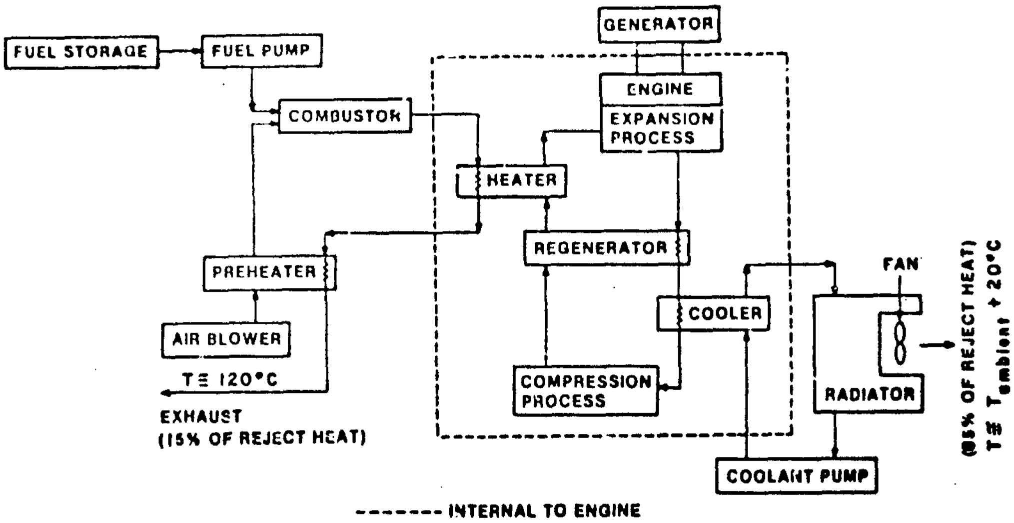


Fig. 1. Stirling Powered Generator Set Flowsheet

The BTSE project has been supported by the Department of Energy for improved reliability potential of several components incorporated in the engine. The engine has not been built and tested, therefore conclusions presented in this report are based upon the final set of component drawings supporting documents delivered by Stirling Thermal Motors, Inc. (STMI), and performance projections made by STMI based on the final design. The design code used to calculate performance predictions was developed by Philips and extensively validated against many different Stirling engines.

The BTSE design features that offer enhanced reliability are described and performance projections made. It is concluded that the present design would be suitable for a 30 kW electric generator set that would be comparable to current diesel driven sets in terms of power quality, size, and weight (size and weight improvement is possible). A scaled-up version of the present design in a 60 kW electric generator set appears most appropriate for Air Force requirements. Fuel consumption would be improved and any logistic fuel could be used. The BTSE (see Fig. 2) is expected to operate as quietly as previous Stirling engines (see Chapter II) and exhibit low thermal emissions. Use of the BTSE for a 15 kW set is considered and trade-offs are discussed (benefits due to increased standardization and increased life versus the disadvantages of increased cost and weight of using the same engine for both 15 kW and 30 kW sets). Standardization is also possible using the scaled-up engine for both 60 kW and 30 kW generator sets.

SECTION II

DESCRIPTION OF BASE TECHNOLOGY STIRLING ENGINE (BTSE)

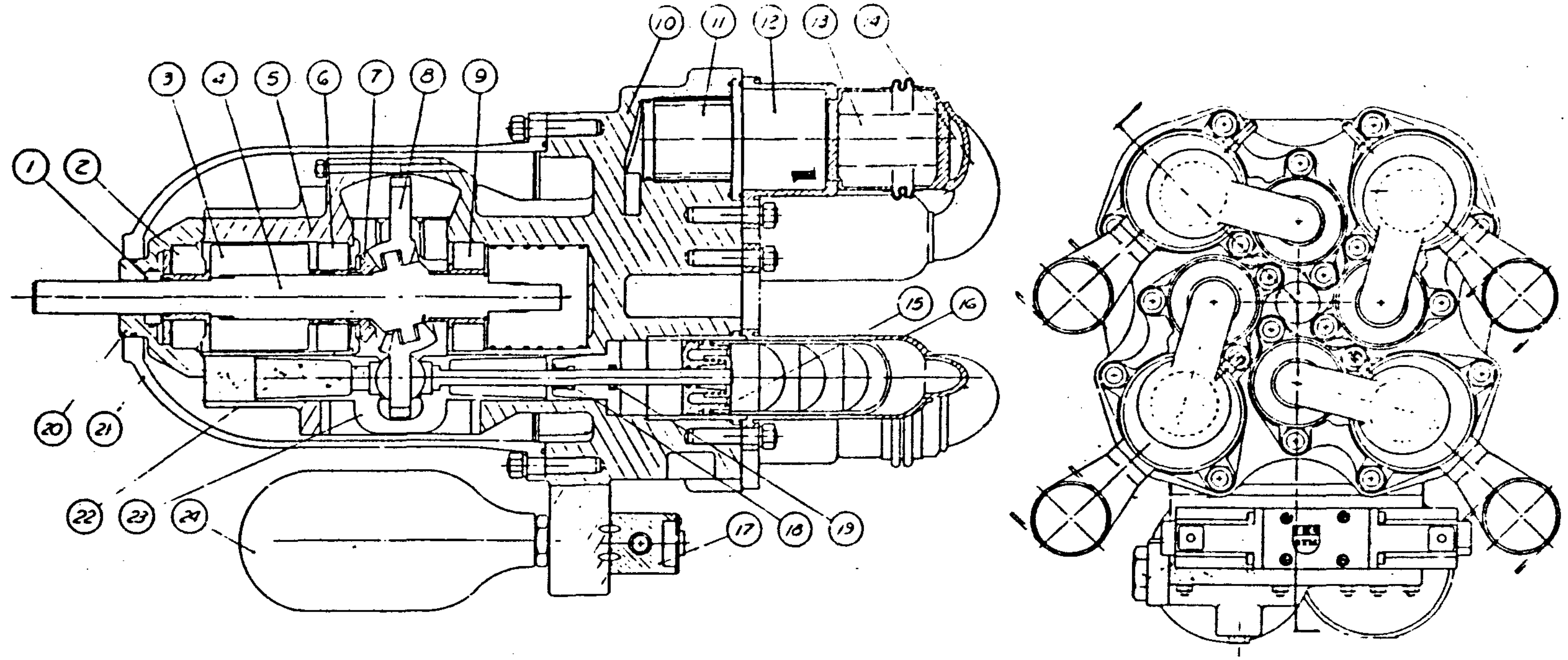
The BTSE, a nominal 25 kW Stirling engine, is shown in Fig. 2. Although the engine itself is an advanced concept in Stirling technology, it embodies development by N.V. Philips of the Netherlands during the period 1938 through 1980. This work was carried to its present state under subcontract to Argonne National Laboratory by Stirling Thermal Motors, Inc. (STMI) of Ann Arbor, Michigan. STMI is headed by Dr. Roelf Meijer, formerly Director of Stirling engine development at N.V. Philips. Argonne has also supported this work through design reviews and participation in component structural analysis. The deliverables of this work have been a full set of component drawings (with certain thermodynamic section dimensions withheld to protect proprietary rights) and a report of performance projections based on the final design drawings (performance projections are shown in Figs. 5 and 6). Important design parameters are given in Table 1.

1. RELEVANCE OF BTSE DESIGN TO MOBILE ELECTRIC POWER REQUIREMENTS

The importance of the BTSE, and the principal reason for Department of Energy support, is that new design approaches are offered to problem areas that have limited Stirling reliability. The problems associated with the BTSE design are felt to be more amenable to resolution through conventional design and manufacturing practices. The BTSE approach offers potentially higher reliability with favorable performance characteristics.

a. BTSE Features that Enhance Reliability

The BTSE design has the potential for improved reliability of heater heads, main seals, and engine controls, and evolves from concepts being investigated by Philips prior to ending their Stirling R&D. The design approach is quite different from that of Philips licensees, notably United Stirling of Sweden (USAB) and MAN of Germany. USAB is presently the supplier of engines to the DOE automotive program and has completed more than 30,000 hours of engine testing and ten years of development, during which the original designs were considerably improved. The BTSE approach attempts to avoid the problems of the USAB (and other) designs rather than trying to resolve innerently severe problems. This is discussed below.



1) Rotating Shaft Seal
2) Thrust Bearing
3) Stroke Converter
4) Main Shaft
5) Rear Crankcase Casting
6) Rear Main Bearing
7) Bevel Gear
8) Swashplate
9) Front Main Bearing
10) Front Crankcase Casting
11) Cooler
12) Regenerator
13) Heater
14) Hot Connecting Duct
15) Piston
16) Cylinder
17) Power Control Valve
18) Oil Scraper
19) Cap Seal
20) Rotating Seal Housing
21) Pressure Hull
22) Cross Head
23) Cross Head Bridge
24) Hydraulic Accumulator

Fig. 2. The Base Engine (Source: Ref. 2)

Table 1. Important Features and Parameters of the Base Engine

Arrangement	Four double-acting cylinders symmetrically arranged about a common axis; one heat exchanger assembly per cylinder
Bore	56 mm
Maximum stroke	48 mm
Overall length	635 mm
Cross-sectional dimensions	Largest cross-section is 300 mm in diameter
Total estimated weight	75 kg
Working fluid Helium	
Mean cycle pressure	11 MPa
Heater temperature	800°C
Power control	Piston stroke variation by means of a variable swashplate with a maximum angle of 22°
Heat transport	Sodium heat pipe
Gas containment	Crankcase pressurized to mean cycle pressure and sealed with a rotating shaft seal
Oil containment	Reciprocating rod oil scraper
Materials	Iron-base CRM-6D, CG-27 heater tube material

Source: Ref. 2.

(1) Heater Head Design

Heater head failures have occurred on Stirling engines since their invention. The usual design has been directly heated, high-pressure tubes with a complex cage geometry needed to provide sufficient heat transfer surface area in the combustion gas where heat transfer is poor. The heater head failures occur due to both the complexity of this geometry with its many bends and brazed connections, and temperature nonuniformities across the heater head--as much as 100°C, even in the best designs. Temperature controls must be set for the "hot spot" in the heater head since heater heads are usually operated near their metallurgical limits.

Details of the BTSE heater can be seen in Fig. 3. The heater tubes are of a simple curved design whose small dimensions are possible through use of a heat pipe for indirect heating. Heat transfer on the outside of the tubes is now essentially infinite, and tube size may be reduced accordingly. Each cylinder is provided with a separate heat pipe to transport heat from the combustor to the heater. The heater now is approximately the same size as the cooler, as may be observed by referring to Fig. 1. In the usual design, the heater is several times larger. Heat transfer is still poor at the evaporator

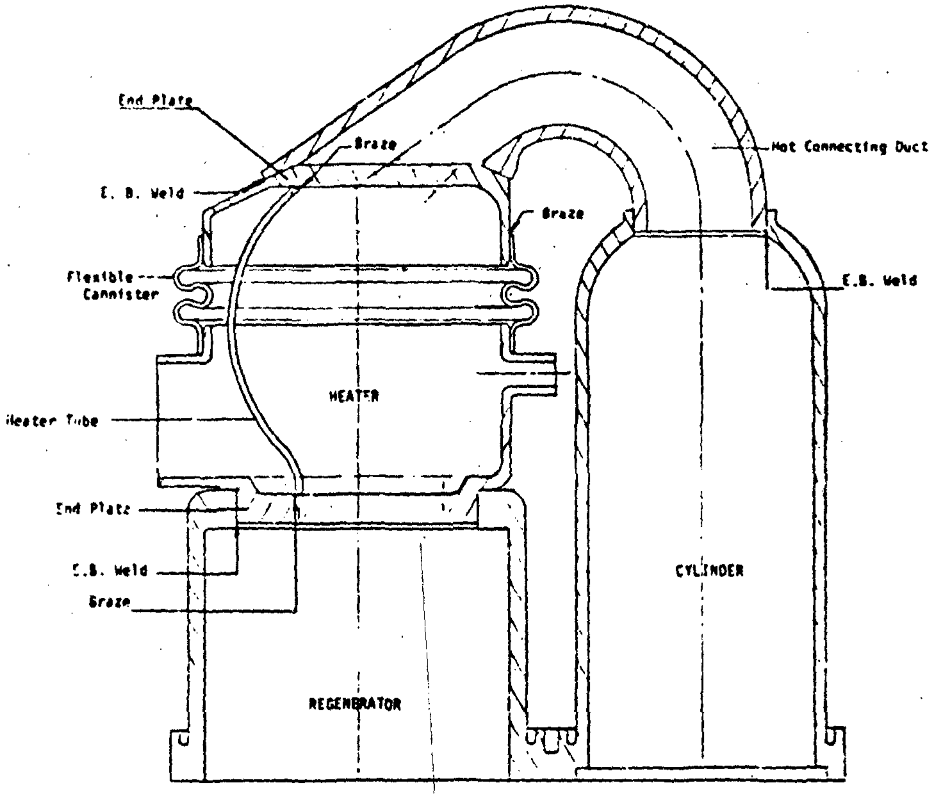


Fig. 3. Heat-Exchanger-Stack Configuration
(Source: Ref. 2)

end of the heat pipe (in the combustor), where larger surface area must be provided. The engine heater head is now protected by the heat pipe from local hot spots and is, in addition, much simpler and stronger.

The evaporator section must be designed for the harsh environments of the combustor but, again, use of a heat pipe is beneficial: the evaporating sodium will tend to make temperature uniform and, since the heat pipe operates at uniform pressure, the structure in the combustor does not have to be sized to contain high pressure (up to 3000 psi in directly heated Stirling engines).

An additional reliability consideration is that in case of failure of the hot side heat exchanger (in this case the end of the heat pipe in the combustor) the engine will not shut down. Each of the four cylinders is served by a separate heat pipe so a failure would reduce heat input to the engine by one-fourth.

The disadvantages of the BTSE heater are the additional complexity of the indirect heater system and the safety problems associated with having a small amount of liquid sodium in the system (on the order of 100 grams total). This problem is presently perceived as small for the following reasons:

- The amount of sodium is small.
- The sodium is not pressurized (at approximately atmospheric pressure when the heat pipe is operating).
- In the event of a failure (a breach in the heat pipe), only a portion of the sodium will migrate from the breached heat pipe--the sodium at the cold end is likely to remain in the heat pipe.

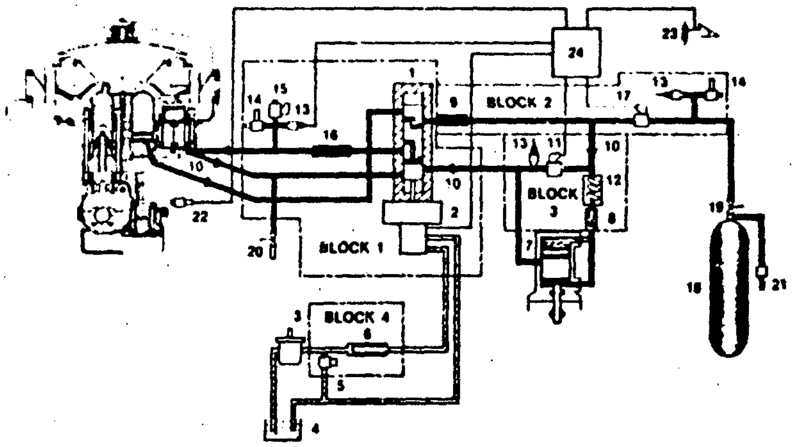
The potential problems of using sodium heat pipes must be carefully assessed and shown not to present a significant risk in the mobile electric power environment.

(2) Power Control/Drive Mechanism

Power control of Stirling engines is usually accomplished by adding and removing working fluid to each cylinder at precise points in the cycle. Thus, two tubes are connected to each reservoir with a complex piping network of valves, controls and a reservoir required. This system is complex and costly, and subject to leaking and other problems. A typical pressure control system is shown in Fig. 4.

The BTSE uses a circular swashplate to transfer reciprocating piston motion to rotary shaft motion. Sliders ride on the swashplate and make the connection to the pistons. The swashplate, sliders and piston rod are shown in Fig. 2. This type of drive has been used extensively in compressors and pumps, but not in prime movers. The BTSE incorporates a swashplate whose angle (relative to the main shaft) can be varied to provide power control. In Fig. 2, the swashplate is shown at 90° relative to the main shaft--no power would be transmitted. At 68° full power would be transmitted.

Power control is achieved with a hydraulic system that varies the swashplate angle; it is a simpler and potentially more reliable system. The engine remains at constant pressure during all power settings, thus reducing failure due to pressure cycling but increasing creep (Table 2).



1. SUPPLY, DUMP AND SHORT-CIRCUIT SPOOL VALVE
2. ELECTRO-HYDRAULIC SERVO ACTUATOR
3. OIL PUMP
4. OIL TANK
5. CONSTANT PRESSURE VALVE
6. OIL FILTER
7. HYDROGEN COMPRESSOR
8. HYDROGEN FILTER
9. HYDROGEN FILTER
10. CHECK VALVE
11. COMPRESSOR SHORT-CIRCUITING SOLENOID VALVE
12. HYDROGEN COOLER
13. PRESSURE TRANSDUCER
14. SAFETY VALVE
15. EXTERNAL DUMP VALVE
16. HYDROGEN FILTER
17. SHUT-OFF VALVE
18. HYDROGEN STORAGE TANK
19. SHUT-OFF VALVE
20. HYDROGEN REFILLING VALVE
21. TEMPERATURE MELTING DISC
22. SPEED TRANSDUCER
23. ACCELERATOR POTENTIOMETER
24. ELECTRONICS

Fig. 4. Conventional Stirling Power Control by Changing Cycle Pressure (United Stirling Engine) (Source: Ref. 3)

(3) Working Fluid Main Seal

Sealing the working fluid of most Stirling engines is a severe problem since each piston rod is sealed between mean cycle pressure above the seal and ambient pressure in the engine crankcase. Thus, there are several seals and each must seal a high pressure light gas under reciprocating service. In order that the seals function under these conditions, they must be well lubricated by pumping pressurized oil to the seals. This aggravates the difficult problem of preventing oil from entering the working space of the engine, a common failure mode.

The BTSE contains only a single main seal around the rotating shaft as it exits the crankcase. The crankcase is maintained at mean cycle pressure as is the space above an oil scraper on each of the four piston rods. These scrapers do not have to support a differential pressure and act only to eliminate any crankcase oil from entering the working space. Since the path from the crankcase is long, the likelihood of failure due to oil contamination of working fluid is less with the BTSE design than the usual Stirling design.

The single main rotating shaft seal is shown in Fig. 2. It seals between pressurized oil in the crankcase and ambient pressure. Seal reliability is thus enhanced by the following:

- Only one main seal is used rather than one per cylinder.
- The seal is on a rotating shaft rather than reciprocating.
- The high pressure medium is oil rather than a light gas (helium or hydrogen).

b. BTSE Efficiency

Calculated performance of the BTSE is shown in Fig. 5. These projections were made using a well-validated design code (developed by N.V. Philips) and should be a conservative estimate of actual engine operation.

The calculated power in Fig. 5 does not include combustor-related losses or auxiliaries such as blowers and pumps. Assigning an efficiency of 90% to the combustor (reasonable for a well-designed combustor with preheater)

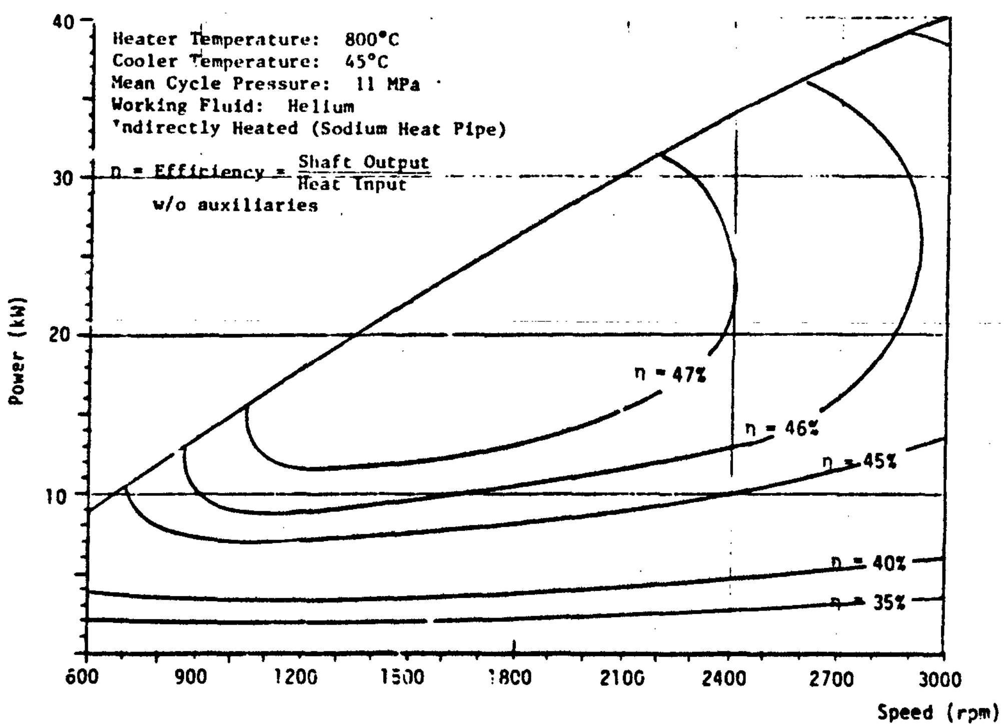


Fig. 5. Performance Map of Base Technology Stirling Engine (Mean Pressure: 11 MPa) Showing Lines of Constant Efficiency

and allowing 1600 W for auxiliaries would lower the maximum efficiency shown in Fig. 5 from 47% to 40% (corresponding to a BSFC of 0.35 lb/Hp-Hr with diesel fuel). This efficiency is very good for an engine in this power range and remains high over a wide operating range. Since generating sets spend a high percentage of their duty cycle at part load, this high part load efficiency is important.

c. Standard Families of Generator Sets

Figure 5 indicates that the current BTSE design would be suitable for use in a 30 kW electric generating set (considering only maximum power capacity). Figure 6 shows the effect of reducing the mean pressure to 6.3 MPa (60 atmospheres) from the 11 MPa level of Fig. 5. Operating the engine at this level would make it suitable for use in a 15 kW set and the same engine could be used for both 15 and 30 kW sets, giving the advantage of reduced parts inventory, manuals, and training procedures.

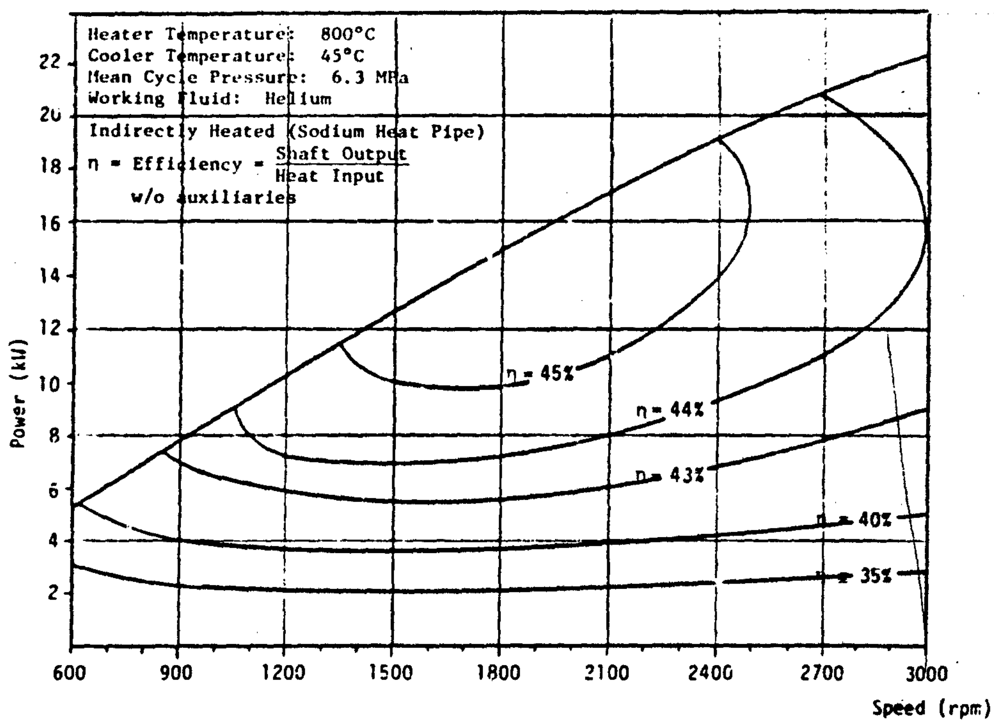


Fig. 6. Performance Map of Base Technology Stirling Engine with Reduced Mean Pressure (6.3 MPa) Showing Lines of Constant Efficiency

Reducing the pressurization in this way produces a different effect than operating a diesel at part load. Comparing Figs. 5 and 6 shows that performance is not degraded at the lower level, nor does engine responsiveness to load change, as would be the case if a diesel engine were operated at half power over the same speed range as full power.

A beneficial effect of operating at lower pressure is the increase in life of bearings and hot-side components whose life is limited by creep (maximum allowable creep 1%). Table 2 shows the effect of pressurization on life.

The benefits of standardizing the 15 kW and 30 kW family of generator sets with the same Stirling engine would have to be traded off against the higher cost/kW and weight/kW of the lower pressure engine. This new means of accomplishing standardization should be examined for its benefits.

Table 2. Creep Rupture Life of BTSE Hot Parts

	Creep Rupture Life (hours)	
Component (Material)	11 MPa	6.3 MPa
Regenerator (CRM-6D)	10^5	10^{10}
Cylinder (CRM-6D)	10^5	10^8
Heater Tubes (CG-27)	10^6	10^7

Source: Ref. 2.

SECTION III

COMPARISON OF BTSE WITH PRESENT 30 kW GENERATOR SET

Characteristics of a standard 30 kW precise power MEP engine generator are given in Ref. 4 and reproduced in Table 3 for ease of comparison. A discussion is now given of possible important consequences of using the BTSE in a 30 kW set to replace the existing unit.

1. PHYSICAL CHARACTERISTICS

a. Weight

The weight of the standard set is 1293 kg. The weight of the 6 cylinder diesel engine in this set is approximately 450 kg or one-third of the total set weight. The BTSE bare engine weight is 75 kg and total weight with combustor would be approximately 100 kg. Thus, significant weight reduction would indeed be possible with use of the BTSE. However, it is also possible to obtain diesel engines in this power range that are much closer to the expected system weight of the BTSE (a water-cooled Volkswagen diesel industrial engine, Type 068.2, rated at 34 kW continuous, weighs 58 kg). Thus, although weight reduction (relative to the present standard family) would be a favorable aspect of using the BTSE in a 30 kW set, light-weight diesel engines are also available that provide comparable reductions. The weight of a 30 kW generator set powered by the BTSE is estimated to be comparable in weight to the lightest set possible using a liquid-cooled diesel.

b. Dimensions

The comments in Sec. III.1.a regarding weight also apply to size. Size reduction from that shown in Fig. 7 would result from use of the BTSE but, again, comparable size reduction could be attained with a diesel system if desired. In neither case would the size reduction be enough to allow transporting two new sets in place of one current set.

Table 3. Characteristics of Standard 30 kW Engine Generator Set

Classification	
Description:	30 kW @ 0.8 power factor, 50/60 Hz, 120/208 V, 240/416 V
	Model: MEP-104A; NSN: 6115-00-118-1247; Spec: MIL-G-52884/4; Type: I (tactical); Class: 1 (precise); Mode: I (50/60 Hz)
Physical Characteristics	
Dimensions:	See Fig. 7.
Weight:	2850 lbs (1293 kg).
Mobility:	Fully housed. Mounted on skid base. Lifting and tie-down attachments provided. Fork lift provision.
Engine:	Diesel. Std: MIL-STD-1410. Horsepower: 57 @ 1800 RPM. No. of cycle: 6. Cycle 4. Liquid cooled. 24 VDC electric start. Operating speed: 50Hz: 1500 RPM, 60 Hz: 1800 RPM. Fuel tank capacity: 26 gallons (approx. 8 hours at rated load). Fuel pump lift: 12 feet.
Fuel:	Primary: VV-F-800: Diesel Fuel Oil, types DF-1, DF-2 and DF-A. Emergency Fuel: MIL-T-5624, Aviation Turbine Fuels, grades JP-4 and JP-5.
Electrical:	Drip proof generator enclosure. Capable of parallel operation. Fungus and moisture treatment. Solid state voltage regulator. Brushless rotary exciter.
Voltage Connection:	60 Hz: 120/208 V, 3 phase, 4 wire. 240/416 V, 3 phase, 4 wire. 50 Hz: 120/208 V. 3 phase, 4 wire. 240/416 V, 3 phase, 4 wire.
Protective Devices:	Short circuit protection. Overvoltage protection. Overload protection. Reverse power protection. Low oil pressure cut-off switch. High temperature cut-off switch. Low fuel level cut-off switch. Overspeed cut-off switch.
Instrumentation:	Voltmeter. Frequency meter. Ammeter. Hourmeter. Wattmeter (% load). Oil pressure gage. Battery charging ammeter (% current). Fault indicating system. Coolant temperature indicator. Fuel level.

Table 3. (Cont'd)

Functional/Operational Characteristics

Reliability: Mean Time Between Failures (MTBF): 370 hours (specified).

Fuel Consumption: 3 gph at rated load.

Electro-magnetic Interference: Supression to MIL-STD-461 limits.

	Voltage	Frequency
Steady State Stability (variation)		
Short Term (30 sec)	1% Bandwidth	0.5% Bandwidth
Long Term (4 hours)	2% Bandwidth	1% Bandwidth
Transient Performance		
Application of rated load	15% Dip	1.5% Undershoot
recovery	0.5 Sec	1 Sec
Rejection of rated load	15% Rise	1.5% Overshoot
recovery	0.5 Sec	1 Sec
Application of simulated motor load	30% Dip	
recovery	0.7 Sec	
Waveform		
Maximum Deviation Factor	5%	
Individual Harmonic	2%	
Regulation	1%	0.25%

Adjustment Range for Standard Voltage Connections

120/208 V Conn: 60 Hz: 197 to 240 V. 50 Hz: 190 to 213 V.
240/416 V Conn: 60 Hz: 395 to 480 V. 50 Hz: 380 to 426 V.

Frequency Adjustment Range:

58 to 62 Hz. 48 to 52 Hz.

Table 3. (Cont'd)

Environmental Data

Power Output at Environmental Conditions:

30 kW, 60 Hz, Sea level: Minus 25°F (-31.7°C) to plus 125°F (+51.7°C)
30 kW, 60 Hz, 5000 feet: Minus 25°F (-31.7°C) to plus 107°F (+41.7°C)
25 kW, 50 Hz, Sea level: Minus 25°F (-31.7°C) to plus 125°F (+51.7°C)
25 kW, 60 Hz, 5000 feet: Minus 25°F (-31.7°C) to plus 107°F (+41.7°C)
Winterization system extends lower temperature limit to minus 65°F (-53.9°C).

Shock and Rough Handling: 10 mph railroad impact. 12 inch end drop. Truck and trailer transportation.

Attitude: Operate with base level or inclined no more than 15° from level.

Noise Level: 82 dbA @ 25 feet.

Optional Equipment

Sec. 4.4.3 of MIL-STD-633 for additional information on optional equipment.

Description	NSN	Weight lbs (kg)	Effect on Dim (ins)
Wntzn Kit (Fuel Burning)	6115-00-463-9083	45 (20.4)	Int
Wntzn Kit Electric	6115-00-463-9085	40 (18.1)	Int
Wntzn Kit, Aux., Fuel burning	6115-00-463-9098	350 (158.8)	Aux: (41x40x26)
Wntzn Kit, Aux., Elect.	6115-00-463-9099	260 (117.9)	Aux: (36x27x19)
Remote Control Box	6115-00-420-8490	8 (3.6)	Int
Load Bank	6115-00-463-9088		Ext: L+9
Wheel Mounting Kit	6115-00-463-9094	564 (255.8)	Ext: L+8,W+32,H+9
Panel, Auto, Load Transfer, 60 Hz	6115-00-477-7932	825 (374.2)	Aux: (44x19x42)
Spark Arrester Kit	2990-01-032-C756	7.5 (3.4)	Ext: L+12

Reference Documents

Technical Manuals:

Army	Air Force	Marine Corps	Navy
TM TO		NAVFAC	
5-6115-465-12	35C2-3-446-1	TM-06858B/0658590-12	P-8-625-12
5-6115-465-34	35C2-3-446-2	TM-06958B/06859D-34	P-8-625-34
5-6115-465-24P	35C2-3-446-4	SL-4-06858B/06859P	P-8-625-24P
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5-6115-465-12	LO-06858A-06859A-12		

Source: Ref. 4.

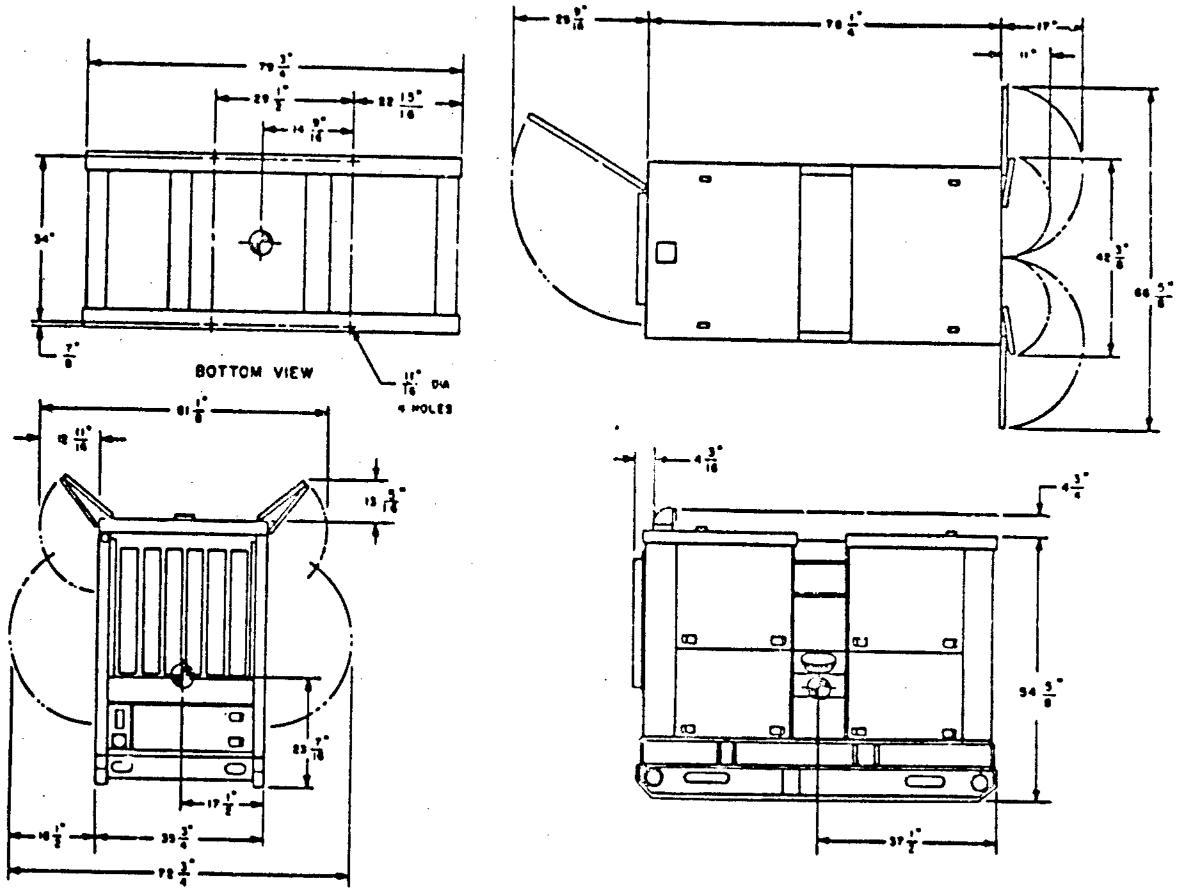


Fig. 7 MEP-104A (30 kW, 50/60 Hz, DED) (Source: Ref. 2)

c. Fuel

The BTSE system would be able to use aviation turbine fuels as well as diesel and gasoline fuels.

d. Protective Devices

In addition to the protective devices listed, a low crankcase pressure switch would be added to indicate when the working fluid (helium) inventory was low.

2. FUNCTIONAL/OPERATIONAL CHARACTERISTICS

a. Mean Time between Failures (MTBF)

The specified MTBF is 370 hours. The design of the BTSE is for 10,000 hours of full load operation before failure (unacceptable creep of regenerator). However, generator set failures are due to electric component failure, combustor failure, and auxiliary component failure which also contribute to eventual MTBF rates.

Design of an engine generator set package containing the BTSE is a specialized task that should be accomplished by one of the companies presently engaged in this business. Failures of Stirling engine systems in the past often have been dismissed as "nonengine related" but actually reflect a lack of attention to system design and selection of standard components that would achieve good reliability.

A goal of a BTSE generator set (and of any Stirling driven set) is that reliability not be degraded in comparison with present units.

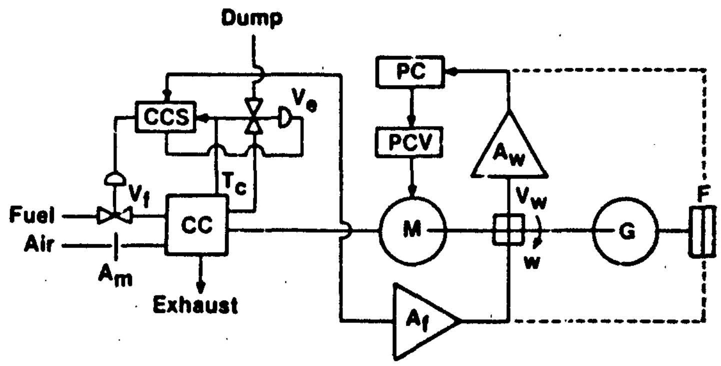
b. Fuel Consumption

With a 30 kW BTSE generator set operating at full load and all system components in good repair, a fuel consumption rate of 2.4 gph is reasonable compared to the 3 gph characterized in Table 3. Improvement in fuel consumption would occur due to the BTSE, more due to improved part-load performance than improved full-load performance, but this is secondary to the primary benefits of fuel flexibility, reduced IR, and reduced noise.

c. Electrical Power Quality

The various measures of power quality (steady state stability, transient performance, waveform, regulation, etc.) are really measures of both the mechanical response of the system and control of the system. A control scheme for a BTSE-driven 30 kW set is shown in Fig. 8, where it is shown that two separate control systems are needed--one for the combustor based on temperature and one for the engine based on output frequency.

The generator output frequency is the most pertinent engine-generator set control characteristic. All of the other parameters can be met provided



CC = Combustion chamber
CCS = Combustor control system
T_c = Temperature sensor
V_f = Fuel flow control valve
A_m = Air metering valve
V_e = Dump valve
M = BTSE
G = Generator
V_w = Speed sensor
A_w = Signal gain circuit conditioning
PC = Power control
PCV = Power control vane (swashplate angle positioner sensor)
A_f = Signal conditioner
F = Frequency sensor (alternator control signal source)

Fig. 8. Candidate Control System

the rotational speed (frequency) is controlled within specifications. The voltage regulation and the deviation characteristics are mostly a function of the generator windings (i.e., stator, excitation field) and magnetics. The frequency will tend to vary with load variations due to small changes in rotational speed. Droop (i.e., undershoot) will tend to occur as the load increases, and rise (i.e., overshoot) will tend to occur as the load is reduced. It is desirable to provide an exact match between power and load to minimize frequency variations.

The motor shaft power is a function of the engine swashplate angle, which is varied by the power control system (PCS). The motor controller will receive a driving signal from the shaft speed sensor. Alternatively, this driving signal can be initiated from an output frequency counter on the generator.

The walls of the combustion chamber, heater head, and engine will have a heat capacity that must be considered in designing the control system. These walls produce a flywheel effect relative to the power demand. There is sufficient heat capacity to supply immediate power demands, or store excess heat following load reduction without causing significant changes in the combustor wall temperature. This combustor wall temperature is maintained by the combustor control system (CCS), which maintains the appropriate fuel/air ratio and fuel feed rate for maximum combustion efficiency.

The PCS functions independent of the CCS. The PCS can supply a signal to the CCS to indicate a change in the output load conditions. This signal may be necessary if the lag time (i.e., response time) of the CCS is too long to accommodate a step change in power demand, e.g., no-load to full-load power. This will depend upon the delay in extracting or storing heat from or in the engine itself.

A heat dump mechanism may be required to accommodate a sudden shutdown from full load (e.g., circuit breaker trip, load shedding, etc.) to prevent excessive combustor wall temperatures. This is a function primarily of the heat capacity in the system and must be calculated as a part of the final system design.

(1) Response of BTSE to Load Change

While output quality (frequency control) is ultimately determined by the electrical control system, a lower bound is set by the mechanical response of the BTSE hydraulically supplied variable angle swashplate. As explained in Sec. II.2, BTSE power is regulated by varying the angle of the swashplate relative to the driveshaft.

The swashplate and its associated hydraulic system were designed to accomplish full movement of swashplate rotation (22°) in 0.2 sec. This mechanical response sets a lower limit on control system response. Providing output quality required for precise power (Class I) is considered possible, but requiring careful control system design.

This is a key area which cannot be resolved at present since the BTSE has not been built and tested. There do not appear to be insurmountable difficulties in achieving the precise control desired with available electronic control components.

3. ENVIRONMENTAL CHARACTERISTICS

a. Power Output at Environmental Conditions

The BTSE, like other Stirling engines, is not connected to the environment except through heat exchangers. Thus the combustor system is designed to provide adequate combustion air at extremes of altitude and temperature with no derating of the engine. The lower temperature limit affects the cooling system and, as in diesel-powered sets, precautions must be taken against coolant freezing. Operation of diesel sets in extreme cold can result in the engine running at temperatures well below design conditions (not enough heat is generated by combustion at part load to bring the engine to normal operating temperatures). This is less likely to occur with the BTSE since low combustion air temperatures do not directly cool the engine as with IC engines.

b. Shock and Rough Handling

Shock and vibration specification have not been developed as part of the BTSE design. The ability of the BTSF to withstand shock and rough handling would depend to a great extent upon the generator set packaging. Care must be taken in packaging to avoid breach of the sodium heat pipes.

c. Attitude

The ability to operate at 15° from level would not be a problem with the present BTSE design.

d. Noise Level

The BTSE will emit little discernible noise (a possible noise source is a clicking of the piston sliders on the swashplate as thrust reverses during the cycle--this must be determined experimentally). Noise is primarily due to the combustion air blower, combustion exhaust, and the cooling fan.

The combustion process is continuous (as in turbines, but much lower flow rates are required since the air does not provide cooling) and the pressure level in the engine varies only by a factor of two during operation.

This eliminates the two most important sources of noise found in internal-combustion engines. Extreme quietness is projected for a Stirling-engine-driven heat-pump system presently being developed in Japan using a 30 kW Stirling engine having a specification of 60 dB at 1 meter.[6]

SECTION IV

OPTIMUM SIZE FOR AF APPLICATION

The results of a recent Air Force mobile power system analysis[7] defined nine major AF mobile power needs shown in Table 4.

The present BTSE design is for 40 kW maximum power and therefore does not directly apply to any of the above applications. The design however could be scaled to the 5 kW, 100 kW, and 250 kW sizes. A 500 hp (373 kW) conceptual design study was performed earlier[8] based upon the design concepts embodied in the BTSE.

Since the 60 kW power range has the most apparent impact on AF needs (at least in terms of the number of sets in use) a scaled-up version of the BTSE should be built and tested. If the 60 kW set is successful, then an experience base will be established for developing 100 kW and 250 kW units. The question of developing the BTSE design for 5 kW application is largely an economic one since at some size, cost will not scale down with size (for example, a 5 kW engine might cost the same to manufacture as a 10 kW engine) leading to excessive costs in terms of dollars/kW in the lower power range. This determination has not been made at the present time however.

1. EXPECTED WEIGHT OF 60 kW BTSE SET

Table 5 gives the approximate weight of several standard generator sets with breakdowns of weight distribution for the diesel engine sets. The gas turbine driven system is much lighter than the diesel sets (by a factor of four in this example). A 60 kW Stirling set using the BTSE design would fall between the total weights of the gas turbine set and the diesel set, potentially being several hundred pounds lighter than the diesel engine of this example.

2. EXPECTED NOISE LEVEL OF 60 kW BTSE SET

Some data on noise from selected engine generator sets are given in Table 6. The data for the 3.0 Stirling refer to the 3 kW Stirling set described in Reference 1. A conservative estimate of noise level from a Stirling set based upon past experience is that it would be quieter than a "silenced" diesel engine driven set.

Table 4. Major AF Mobile Power Requirements

Type of Set	AF Application
5 kW Precise	TACPs,[a] MAC,[b] CCTs[c]
5 kW Utility	General purpose
60 kW Precise	TACS[d]
60 kW Precise	Flightline
60 kW Utility	General purpose
100 kW Precise	TACS
100 kW Utility	General purpose
250 kW Utility	General purpose
750 kW Prime	Rapid deployment support

Source: Ref. 2.

[a]Tactical Air Control Party.

[b]USAF Military Airlift Command.

[c]Combat Control Team.

[d]Tactical Air Control System.

Table 5. Weight of DOD[a] Generator Set Assemblies and Components (lbs) (approximate)

	DED[b] 15 kW	DED 30 kW	DED 60 kW	GTED[c] 60 kW	DED 100 kW	DED 200 kW
Set (Total)	2,475	2,925	4,350	950	7,000	10,500
Generator	490	640	1,020		2,500	3,400
Engine	825	1,050	1,423		2,125	4,350
Skid base	325	380	556		1,100	1,300
Radiator	40	50	67		90	125
Control cabinet	55	55	55		55	55
Sheet metal, current transformers, wiring, batteries, tanks, relays, excitor, etc.	740	750	1,229		1,130	1,270

[a]Department of Defense.

[b]Diesel-engine driven.

[c]Gas-turbine-engine driven.

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Control cabinet	55	55	55		55	55
Sheet metal, current transformers, wiring, batteries, tanks, relays, excitor, etc.	740	750	1,229		1,130	1,270

[a]Department of Defense.

[b]Diesel-engine driven.

[c]Gas-turbine-engine driven.

Table 6. 100 Meter[a] Noise Levels of Selected Engine-Generator Sets

Octave Band Center Frequency (Hz)	Sound Pressure Level in dB. Re: 0.0002 Microbar					
	Engine Generator Set (kW)					
	1.5 GED	3.0 Stirling	30.0 DED Standard	30.0[b] DED Silenced	60.0 DED Standard	60.0[c] DED Silenced
53	56.5	42	63.1	63.1	62.1	58.1
106	55.5	31	69.1	66.6	72.1	59.1
212	56.5	28	69.1	63.1	64.1	59
425	50.5	26	59.1	43.1	66.1	59.1
850	50	27	58.1	41.1	64.6	47.6
1700	50.5	30	54.1	37.1	60.1	46.1
3400	44.5	21	48.6	35.1	53.1	44.1
6800	40	27	40.1	26.1	50.6	39.1

[a]Extrapolated from 10 ft or 25 ft. Data assuming free-field conditions.
[b]Experimental Kit, 190 lb weight, $2300 estimated cost (1978).
[c]Experimental Kit, 450 lb weight.

3. FUEL FOR 60 kW BTSE SET

The BTSE set is expected to use the same fuels as present gas turbine sets, both primary and emergency classifications.

4. COLD START-UP TIME

The calculated time for the heater head to reach operating temperature (800°C) is 35 to 45 sec. During this period the engine is not operating and the sodium heat pipe and engine heater head come up to temperature.[7] This process is primarily sonic-limited, as the vapor flow in the heat pipe becomes choked immediately.

Overall start-up times of the present BTSE design are comparable to that of directly heated Stirling engines (15 to 20 seconds for the automotive engine) and compares favorably to diesel engines.

5. STANDARDIZATION OF 60 kW AND 40 kW GENERATOR SETS

Standardization of 30 kW and 15 kW sets are discussed in Sec. II.c using the current BTSE design. The same standardization of 60 kW and 40 kW sets could be accomplished if a 60 kW version of the BTSE were developed. The same engine, auxiliaries, and packaging would be used with a different generator and the engine operating with reduced cycle pressure as described in Sec. II.c. The benefits are increased standardization and life while the penalty is increased cost/kW and weight/kW.

SECTION V

CONCLUSIONS

The BTSE design has potentially good reliability and offers the following benefits as a prime mover in mobile electric power generator sets in the size range 15 kW to 250 kW.

- Fuel flexibility (similar to that possible with gas turbine sets).
- Good specific weight (comparable to the best achievable with diesel sets).
- Increased standardization.
- Low noise (better than that achievable with silenced diesel sets).
- Low IR -- both because the majority of heat is emitted through the radiator at already low temperature and because the engine is somewhat more efficient than current sets and consequently releases less heat.
- Good efficiency (comparable to the best achievable by diesels in this power range). A characteristic of Stirling engines is that efficiency improves at part load rather than remaining constant as with diesels or falling off rapidly as with gas turbines.

The BTSE is still a paper engine at this time although the technology reflects the many years N.V. Philips spent on Stirling development and the years this project was supported by Argonne National Laboratory. Thus, while there is the advantage of being able to modify the design to meet particular needs of this application, no actual performance and reliability data exist.

This review, while preliminary since test data are not available, has not determined any deficiencies in the BTSE design that would rule out its use in mobile power sets. Areas of concern are the use of sodium heat pipes (although the sodium inventory is small), and the ability to achieve precise power control required of Class 1 sets. The transient response of the hydraulic control system of the BTSE appears adequate to meet these requirements if a suitable electronic system is obtained.

Development is necessary to build and test the BTSE before answers can be obtained to the key areas of concern identified in this report. A decision to continue this development should include consideration of other power conversion needs, such as space power or facilities power, that would benefit from a successful development program.

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